

PCT/EP 97/07011

60/032864

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UNITED STATES DEPARTMENT OF COMMERCE
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PRIORITY DOCUMENT

January 8, 1998

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.

APPLICATION NUMBER: 60/032,864

FILING DATE: December 13, 1996

IP AUSTRALIA

24 JUN 1998

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P. R. GRANT

Certifying Officer

PATENT APPLICATION SERIAL NO. **60/032864**

U.S. DEPARTMENT OF COMMERCE
PATENT AND TRADEMARK OFFICE
FEE RECORD SHEET

010 UT 01/30/97 60032864
1 114 150.00 CK 573.00

PTO-1556
(5/87)

60/032864



Appendix A

 PTO/SB/16 (2-93)
 Approved for use through 04/1/98. OMB 0411-0017
 Patent and Trademark Office, U.S. DEPARTMENT OF COMMERCE

PROVISIONAL APPLICATION COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION under 37 CFR 1.53 (b)(3).

| | | | | |
|--|---|------------------|---|--|
| Docket Number | | 573.0P | Type a plus sign (+) under this box | + |
| INVENTOR(S)/APPLICANT(S) | | | | |
| LAST NAME | FIRST NAME | INITIALS | RESIDENCE CITY AND OTHER STATE OR FOREIGN COUNTRY | |
| Nicolaou | Kyriacos | C. | La Jolla, California C+ | |
| Sarabia | Francisco | | La Jolla, California C- | |
| Ninkovic | Sacha | | San Diego, California C- | |
| TITLE OF THE INVENTION (See instructions on back) | | | | |
| SYNTHETIC APPROACHES FOR EPOTHILONE A AND RELATED ANALOGS | | | | |
| CORRESPONDENCE ADDRESS | | | | |
| THE SCRIPPS RESEARCH INSTITUTE, Office of Patent Counsel 10550 North Torrey Pines Road, TPC-8, La Jolla | | | | |
| STATE | CA | ZIP CODE | 92037 | COUNTRY United States |
| ENCLOSED APPLICATION PARTS (check all that apply) | | | | |
| <input checked="" type="checkbox"/> | Specification | Number of Pages | 24 | <input type="checkbox"/> Small Entity Discount |
| <input checked="" type="checkbox"/> | Drawing(s) | Number of Sheets | 7 | <input type="checkbox"/> Other (specify): |
| METHOD OF PAYMENT (check all that apply) | | | | |
| <input checked="" type="checkbox"/> | A check or money order is enclosed to cover the Provisional Filing fee | | | PROVISIONAL FILING FEE AMOUNT (\$) 150.00 |
| <input type="checkbox"/> | The Commissioner is hereby authorized to charge filing fee and credit Deposit Address Payment | | | |

additional name:
are attached

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☐ No.☒ Yes, the name of the U.S. Government agency and the Government accession number are:

NIH CA58336

Respectfully submitted,

SIGNATURE

D. C. Lewis

Date 12/13/96

TYPED or PRINTED NAME Donald G. Lewis

REGISTRATION NO. (if appropriate)

28,636

☒ Additional inventors are being named on separately submitted sheets attached hereto.

PROVISIONAL APPLICATION FILING ONLY

Before Filing Statement: This form is submitted to you 3 hours to expiration. There will very expediting time the date of the expiration date. Any application on the expiration of time you are required to continue the form, submit to you to the Office of Assistant Secretary and Registration Office, Patent and Trademark Office, Washington, DC 20531, and to the Office of Information and Regulatory Affairs, Office of Management and Budget (Printed 04/1/93), Washington, DC 20503. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patent, Washington, DC 20531.

Continuation of Appendix A (additional inventors)

| | |
|------------------------------|------------------------------|
| <u>Yang, Zhen</u> | <u>San Diego, California</u> |
| <u>He, Yun</u> | <u>San Diego, California</u> |
| <u>Vourloumis, Dionisios</u> | <u>San Diego, California</u> |
| <u>Vallberg, Hans</u> | <u>San Diego, California</u> |



60/032864

Attorney's Docket No. 573.0P

PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of: K.C. Nicolaou, Francisco Sarabia, Sacha Ninkovic,
Zhen Yang, Yun He, Dionisios Vourloumis, Hans Vallberg

For: SYNTHETIC APPROACHES FOR EPOTHILONE A AND RELATED ANALOGS
Box Provisional Patent Application
Commissioner of Patents and Trademarks
Washington, D.C. 20231

COVER SHEET FOR FILING PROVISIONAL APPLICATION
(37 C.F.R. § 1.51(2)(i))

WARNING: "A provisional application must also include a cover sheet identifying the application as a provisional application. Otherwise, the application will be treated as an application filed under § 1.53(b)(1)." 37 C.F.R. § 1.53(b)(2)(i).

NOTE: "A complete provisional application does not require claims since no examination on the merits will be given to a provisional application. However, provisional applications may be filed with one or more claims as part of the application. Nevertheless, no additional claim fee or multiple dependent claims fee will be required in a provisional application." Notice of December 5, 1994, 59 FR 63951, at: 63953.

"Any claim filed with a provisional application will, of course, be considered part of the original provisional application disclosure." Notice of April 14, 1995, 60 Fed. Reg. 20,195, at: 20,209.

NOTE: "A provisional application shall not be entitled to the right of priority under § 1.55 or 35 U.S.C. 119 or 365(a); or to the benefit of an earlier filing date under § 1.78 or 35 U.S.C. 120, 121 or 365(c) of any other application." 37 C.F.R. § 1.53(b)(2)(ii).

NOTE: "No information disclosure statement may be filed in a provisional application." 37 C.F.R. § 1.51(2)(b). "Any information disclosure statements filed in a provisional application would either be returned or disposed of at the convenience of the Office." Notice of December 5, 1994, 59 FR 63591, at: 63594.

NOTE: "No amendment other than to make the provisional application comply with all applicable regulations, may be made to the provisional application after the filing date of the provisional application." 37 C.F.R. § 1.53(b)(2).

CERTIFICATION UNDER 37 CFR 1.10

I hereby certify that this correspondence and the documents referred to as attached herein are being deposited with the United States Postal Service on December 13, 1996 (date), in an envelope as "EXPRESS MAIL, POST OFFICE TO ADDRESSEE" service under 37 C.F.R. 1.10. Mailing Label Number: EM512698968US addressed to the: Commissioner of Patents and Trademarks, Washington, D.C. 20231


Paul K. Richter

(Type or print name of person certifying.)

NOTE: Each paper or fee filed by "Express Mail" must have the number of the "Express Mail" mailing label placed thereon prior to mailing. (37 C.F.R. 1.10(d))

WARNING: Certificate of mailing (first class or routine transmission procedures of 37 C.F.R. 1.81a) cannot be used to obtain a date of mailing or transmission for this correspondence. 37 C.F.R. 1.81a(i)(A).

(Cover Sheet for Filing Provisional Application [23-1]—page 1 of 6)

WARNING: A provisional application may be abandoned by operation of 35 U.S.C. 111(b)(5) on a Saturday, Sunday, or Federal holiday within the District of Columbia. In such case, a nonprovisional application claiming benefit of the provisional application under 35 U.S.C. 119(e) must be filed no later than the preceding day that is not a Saturday, Sunday, or Federal holiday within the District of Columbia. Notice of April 14, 1995, 60 Fed. Reg. 20,195 at 20,262.

1. The accompanying application is a provisional application. (37 C.F.R. § 1.51(a)(2)(i)(A))
2. The name(s) of the inventor(s) is/are (37 C.F.R. § 1.51(a)(2)(i)(B)):

NOTE: While the name or names of the inventors are required in order to accord a provisional application a filing date, a provisional application is not required to be signed by the inventor or the assignee. No oath or declaration is required. Presumably, most provisional applications will be filed by a registered practitioner without a power of attorney being filed. Notice of December 5, 1994, 59 FR 63591, at 63594.

NOTE: "The naming of inventors for obtaining a filing date for a provisional application is the same as for other applications. A provisional application filed with the inventors identified as 'Jones et al.' will not be accorded a filing date earlier than the date upon which the name of each inventor is supplied unless a petition with the fee set forth in § 1.17(f) is filed which sets forth the reasons the delay in supplying the names should be excused. Administrative oversight is an acceptable reason. It should be noted that for a 35 U.S.C. 111(a) application to be entitled to claim the benefit of the filing date of a provisional application the 35 U.S.C. 111(a)(2) application must have at least one inventor in common with the provisional application." Notice of April 14, 1995, 60 Fed. Reg. 20,195, at 20,209.

The term "invention" is typically used to refer to subject matter which applicant is claiming in his/her application. Because claims are not required in a provisional application, it would not be appropriate to reference joint inventors as those who have made a contribution to the "invention" disclosed in the provisional application. If the "invention" has not been determined in the provisional application because no claims have been presented, then the name(s) of those person(s) who have made a contribution to the subject matter disclosed in the provisional application should be submitted. Section 1.45(c) states that "If multiple inventors are named in a provisional application, each named inventor must have made a contribution, individually or jointly, to the subject matter disclosed in the provisional application." All that § 1.45(c) requires is that if someone is named as an inventor, that person must have made a contribution to the subject matter disclosed in the provisional application. When applicant has determined what the invention is by the filing of the 35 U.S.C. 111(a) application, that is the time when the correct inventors must be named. The 35 U.S.C. 111(a) application must have an inventor in common with the provisional application in order for the 35 U.S.C. 111(a) application to be entitled to claim the benefit of the provisional application under 35 U.S.C. 119(e). Notice of April 14, 1995, 60 Fed. Reg. 20,195, at 20,208.

"If all the names of the actual inventor or inventors are not supplied when the specification and any required drawings are filed, the provisional application will not be given a filing date earlier than the date upon which the names are supplied unless a petition, with the fee set forth in § 1.17(q), is filed, which sets forth that the reasons for the delay in supplying the names should be excused." 37 C.F.R. § 1.53(b)(2).

| | | |
|-------------------------------------|---------------------------------------|--|
| 1. <u>Kyriacos</u> (GIVEN NAME) | <u>C.</u> (MIDDLE INITIAL OR NAME) | <u>Nicolaou</u> (FAMILY (OR LAST) NAME) |
| 2. <u>Francisco</u> (GIVEN NAME) | <u></u> (MIDDLE INITIAL OR NAME) | <u>Sarabia</u> (FAMILY (OR LAST) NAME) |
| 3. <u>Sachs</u> (GIVEN NAME) | <u></u> (MIDDLE INITIAL OR NAME) | <u>Ninkovic</u> (FAMILY (OR LAST) NAME) |

Additional names are listed on accompany sheet

(Cover Sheet for Filing Provisional Application (23-1)—page 2 of 6)

3. Address(es) of the inventor(s), as numbered above (37 C.F.R. § 1.51(a)(2)(i)(C)):

1. 9625 Blackgold Road, La Jolla, California 92037
2. 3116 Via Alicante Dr., Apt. G, La Jolla, California 92037
3. 3855 Novel Drive, Apt. 2216, San Diego, California 92122

4. The title of the invention is (37 C.F.R. § 1.51(a)(2)(i)(D)):
Additional address are listed on accompanying sheet

SYNTHETIC APPROACHES FOR EPOTHILONE A AND RELATED ANALOGS

5. The name, registration, and telephone number of the attorney (if applicable) is (37 C.F.R. § 1.51(a)(2)(i)(E)):

Name of attorney: Donald G. Lewis

Reg. No. 28,636 Tel. (619) 678-2937

(complete the following, if applicable)

☐ A power of attorney accompanies this cover sheet.

6. The docket number used to identify this application is (37 C.F.R. § 1.51(a)(2)(i)(F)):

Docket No.: 573.OP

7. The correspondence address for this application is (37 C.F.R. § 1.51(a)(2)(i)(G)):

THE SCRIPPS RESEARCH INSTITUTE, Office of Patent Counsel
10550 North Torrey Pines Road, TPC-8, La Jolla, CA 92037

8. Statement as to whether invention was made by an agency of the U.S. Government or under contract with an agency of the U.S. Government.
(37 C.F.R. § 1.51(a)(2)(i)(H)).

This invention was made by an agency of the United States Government or under contract with an agency of the United States Government.

☐ No.

☒ Yes.

The name of the U.S. Government agency and the Government contract number are:

NIH CA58336

9. Identification of documents accompanying this cover sheet:

A. Documents required by 37 C.F.R. §§ (a)(2)(ii)-(iii):

Specification:

No. of pages 24

Drawings:

No. of sheets 2

B. Additional documents:

☐ Claims:

No. of claims

Note: A complete provisional application does not require claims. 37 C.F.R. § 1.51(a)(2).

☐ Power of attorney

☐ Small entity statement

☐ Assignment

☐ Other

NOTE: Provisional applications may be filed in a language other than English as set forth in existing § 1.52(d). However, an English language translation is necessary for security screening purposes. Therefore, the PTO will require the English language translation and payment of the fee mandated in § 1.52(d) in the provisional application. Failure to timely submit the translation in response to a PTO requirement will result in the abandonment of the provisional application. If a 35 U.S.C. 111(a) application is filed without providing the English language translation in the provisional application, the English language translation will be required to be supplied in every 34 U.S.C. 111(a) application claiming priority of the non-English language provisional application. Notice of April 14, 1995, 60 Fed. Reg. 20,195, at 20,209.

10. Fee

The filing fee for this provisional application, as set in 37 C.F.R. § 1.16(k), is \$150.00, for other than a small entity, and \$75.00 for a small entity.

☐ Applicant is a small entity.

NOTE: "A verified statement in compliance with existing § 1.27 is required to be filed in each provisional application in which it is desired to pay reduced fees." Notice of April 14, 1995, 60 Fed. Reg. 20,195, at 20,197.

11. Small entity statement

☐ The verified statement(s) that this is a filing by a small entity under 37 C.F.R. §§ 1.9 and 1.27 is(are) attached.

12. Fee payment being made at this time

☐ Not enclosed

☐ No filing fee is to be paid at this time
(This and the surcharge required by 37 C.F.R. § 1.16(f) can be paid subsequently).

☒ Enclosed

Total fee enclosed \$ 150.00

13. Method of fee payment

☒ Check in the amount of \$ 150.00

☐ Charge Account No. _____
in the amount of \$ _____

A duplicate of this Cover Sheet is attached.

Please charge Account No. 19-0962 for any fee deficiency.

Date: _____

Tel.: ()

Date: 12/13/96

Reg. No.: 28,636

Tel.: (619) 784-2937

Signature of submitter

OR

Signature of attorney

Donald G. Lewis

(type or print name of attorney)

THE SCRIPPS RESEARCH INSTITUTE

10550 N. Torrey Pines Road

P.O. Address

La Jolla, CA 92037

Names and addresses of additional inventors:

- | | |
|-------------------------|--|
| 4. Zhen Yang | 4158 Decoro Street, No. 2, San Diego, CA 92122 |
| 5. Yun He | 9605 Genesee Avenue, No. H2, San Diego, CA 92122 |
| 6. Dionisios Vourloumis | 4249 Nobel Drive, Apt. 39, San Diego, CA 92122 |
| 7. Hans Vallberg | 4249 Nobel Drive, Apt. 39, San Diego, CA 92122 |



Total Synthesis of Epothilone A: The Olefin Metathesis Approach

604032864

This paper is dedicated to Professor Thomas J. Katz on the occasion of his 60th birthday and in recognition of his pioneering studies on the olefin metathesis reaction.

Zhen Yang, Yun He, Dionisios Vourloumis, Hans Vallberg, K. C. Nicolaou*

[*] Prof. Dr. K.C. Nicolaou, Y. He, Drs. D. Vourloumis, H. Vallberg, Z. Yang

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[**] This work was financially supported by The Skaggs Institute of Chemical Biology and the National Institutes of Health (USA).

Keywords: epothilone, total synthesis, olefin metathesis

Table Content Text

The total synthesis of the antitumor agent epothilone A has been achieved by a highly convergent and flexible strategy involving olefin metathesis as a key step to form the macrocyclic skeleton of the target molecule. The strategy may allow the chemical synthesis of a library of designed epothilones for biological screening.



Epothilon A (1)^[1,2] is an exciting new natural product, isolated from the myxobacteria *Sorangium cellulosum* strain 90, with novel molecular architecture, important biological properties and intriguing mechanism of action. Amongst its biological properties are potent antifungal and selective cytotoxic activities.^[1-4] Its mechanism of action against tumor cells has been attributed to binding and stabilization of microtubules^[4], resembling in that respect, taxol.^[5] Following our recent report^[6] on an olefin metathesis^[7] based approach towards this class of compounds, we now wish to disclose the total synthesis of epothilone A (1) by this novel strategy.

Figure 1 shows the strategic bond disconnections that led to the convergent strategy utilized in this synthesis. As one can surmise by inspection of Figure 1, the plan calls for the construction of the three key building blocks 5, 6 and 10 (Scheme 1), their union and elaboration to the 16-membered macrocycle and final epoxidation. For the present approach, the olefin metathesis step and the selective epoxidation of the $\Delta^{12,13}$ -double bond in the final step were considered, at the outset, both risky and crucial.

Scheme 1 summarizes the construction of the key building blocks 5, 6 and 10. Thus, the synthesis of the requisite carboxylic acid 5 commenced with the known ketoaldehyde 2^[8] which reacted selectively with Brown's allyl isopinocampheyl borane reagent $[(+)\text{-Ipc}_2\text{B(allyl)}]$ ^[9] in ether at -100°C to afford alcohol 3^[10] in 74% yield. Protection of this alcohol with TBSOTf-2,6-lutidine led to the silyl ether 4 in 98% yield. Ozonolytic cleavage of the double bond in the latter compound, followed by NaClO_2 oxidation of the resulting aldehyde gave the targeted carboxylic acid 5 in 75% yield. ^{over} The preparation of the heterocyclic component 10 was carried out from the known thiazole ester 7^[11] by: a) reduction to the corresponding aldehyde (8) (Dibal-H, 90% yield); b) Wittig reaction with $\text{Ph}_3\text{P}=\text{C(Me)CHO}$ to afford the conjugated aldehyde 9 (90% yield); and c) condensation of 9 with $(+)\text{-Ipc}_2\text{B(allyl)}$ in ether at -100°C (95% yield).^[10]

Having secured the requisite building blocks, we then turned our attention to their coupling and further elaboration. Scheme 2 depicts these final stages of the present total synthesis of epothilone A (1). Thus, condensation of the dianion of 5 (2.2 equiv. of LDA, THF, -78 to -40 °C) with aldehyde 6^[6,12] (1.2 equiv) at -78 to -40 °C resulted in the formation of the desired aldol product (11) as the major isomer, together with its 6R,7S diastereomer in high yield and ca 2:1 ratio. Esterification of this mixture with the hydroxy component 10 (2.0 equiv) proceeded in the presence of DCC and 4-DMAP in toluene at 25 °C to afford compound 12 and its 6S,7R 6R,7S diastereomer in 70% overall total yield^[13] from ketoacid 5. The two isomers were chromatographically separated [silica gel, ethyl acetate:hexane (1:5), R_f = 0.29 (12, 45% overall yield from 5), 0.24 (6R,7S diastereomer of 12, 25% yield from 5)], and the major product (12) was taken forward in the synthesis as a pure isomer. Its structure was confirmed by eventual conversion to epothilone A (1). The olefin metathesis reaction of 12 proceeded smoothly in the presence of $\text{RuCl}_2(=\text{CHPh})(\text{PCy}_3)_2$ catalyst^[14] in dilute CH_2Cl_2 solution at 25 °C to afford, in 50% yield, the *Z*-olefin 13,^[15] together with its *E*-isomer (35%)¹⁵. After chromatographic purification [silica gel, benzene:ethyl acetate:hexane (2:1:2), R_f = 0.21 (*Z*-isomer), 0.45 (*E*-isomer)], the silyl group was removed from macrocycle 13 by exposure to CF_3COOH in CH_2Cl_2 at 0 °C to afford the dihydroxy lactone 14 in 98% yield. Finally, selective epoxidation of the $\Delta^{12,13}$ -double bond of 14 was effected with *m*CPBA in CH_2Cl_2 at 0 °C to afford epothilone A (1) in 55% yield [silica gel, methanol: CH_2Cl_2 (1:20), R_f = 0.23], together with its 12 α ,13 α -epoxide isomer [20% yield, silica gel, methanol: CH_2Cl_2 (1:20), R_f = 0.16] and its regioisomer 15 [20% yield, silica gel, methanol: CH_2Cl_2 (1:20), R_f = 0.22, stereochemistry unassigned]. Chromatographically purified synthetic epothilone A (1) exhibited identical properties (^1H and ^{13}C NMR, Mass spec, $[\alpha]_D$, TLC and HPLC) to those of an authentic natural sample.^[16]

The reported total synthesis demonstrates the power of the olefin metathesis reaction in complex molecule construction and renders epothilone A (1) readily accessible. Most importantly, its brevity, convergent nature and flexibility should allow the generation of a diverse epothilone library for further biological investigations. In addition to the olefin metathesis approach reported herein, Figure 1 points to at least two more, distinctly different approaches to epothilones: (a) a macrolactonization approach; and (b) an approach in which an intramolecular aldol reaction may play the crucial role of constructing the macrocyclic skeleton. These and other strategies towards these compounds are currently under investigation in these laboratories.^[17,18]

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- [2] G. Höfle, N. Bedorf, H. Steinmetz, D. Schomburg, K. Gerth, H. Reichenbach, *Angew. Chem.* 1996, 108, 1671-1673; *Angew. Chem. Int. Ed. Engl.* 1996, 35, 1567-1569.
- [3] M.R. Grever, S.A. Schepartz, B.A. Chabner, *Seminars in Oncology* 1992, 19, 622-638.
- [4] D.M. Bollag, P.A. McQueney, J. Zhu, O. Hensens, L. Koupal, J. Liesch, M. Goetz, E. Lazarides, C.M. Woods, *Cancer Res.* 1995, 55, 2325-2333.
- [5] K.C. Nicolaou, W.-M. Dai, R. K. Guy, *Angew. Chem.* 1994, 106, 38-67; *Angew. Chem. Int. Ed. Engl.* 1994, 33, 15-44.
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added

- Limberg, O.M. Böhm, *Chem. Eur. J.* 1996, 2, 1477-1482. For the first total synthesis of epothilone A, see: A. Balog, D. Meng, T. Kamenecka, P. Bertinato, D.-S. Su, E.J. Sorensen, S.J. Danishefsky, *Angew. Chem.* 1996, 108, 2976-2978, *Angew. Chem.* 1996, 35, 2801-2803.
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- [8] Ketoaldehyde 11 was prepared from propionyl chloride according to a literature procedure: T. Inukai, R. Yoshizawa, *J. Org. Chem.* 1967, 32, 404-407.
- [9] U.S. Racherla, H.C. Brown, *J. Org. Chem.* 1991, 56, 401-404
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- [14] P. Schwab, M.B. France, J.W. Ziller, R.H. Grubbs, *Angew. Chem.* 1995, 107, 2179-2181; *Angew. Chem. Int. Ed. Engl.* 1995, 34, 2039-2041.
- [15] Decoupling experiments (^1H NMR, 500 MHz, CDCl_3) revealed coupling constants (J) for $\text{H}_{12}/\text{H}_{13}$ of 11.0 Hz for the *Z*-isomer (13) and 15.0 Hz for the *E*-isomer.

[16] W thank Dr. G. Höfle for kindly providing us with a natural sample of epothilone A

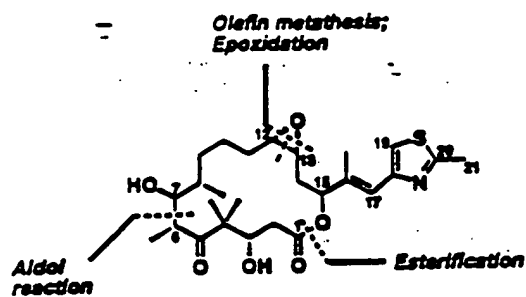
(1).

lab-ic
[17] Selected physical properties of compounds: 12: R_f = 0.29 [silica gel, ethyl acetate:hexane (1:5)]; $[\alpha]_D = -53.4$ ($c = 1.0$, MeOH); IR (film): 3508 (br, OH), 1736 (C(O)O), 1690 (COC), 1650 cm^{-1} (CH=CHCO); $^1\text{H-NMR}$ (500 MHz, CDCl_3): δ = 6.93 (s, 1 H, -C=CH-S-), 6.47 (s, 1 H, -C=CH-C=), 5.81-5.72 (m, 1 H, -CH=CH₂), 5.73-5.65 (m, 1 H, -CH-CH₂), 5.27 (dd, 1 H, $J_1 = 7.0\text{ Hz}$, $J_2 = 6.5\text{ Hz}$, -O-CH-), 5.06 (dd, 2 H, $J_1 = 17.5\text{ Hz}$, $J_2 = 10.0\text{ Hz}$, -CH=CH₂), 4.92 (dd, 2 H, $J_1 = 17.0\text{ Hz}$, $J_2 = 10.5\text{ Hz}$, -CH=CH₂), 4.39 (dd, 1 H, $J_1 = 4.0\text{ Hz}$, $J_2 = 6.0\text{ Hz}$, -(CH₃)₂C-CH-), 3.42 (bs, 1 H, -OH), 3.28 (q, 1 H, $J = 7.0\text{ Hz}$, -CH(CH₃)C(O)-), 3.24 (d, 1 H, $J = 9.5\text{ Hz}$, -CH(OH)), 2.67 (s, 3 H, -S-C(CH₃)=N-), 2.54-2.43 (m, 2 H), 2.43 (dd, 1 H, $J_1 = 4.0\text{ Hz}$, $J_2 = 10.0\text{ Hz}$, -CH₂-COO-), 2.31 (dd, 1 H, $J_1 = 6.0\text{ Hz}$, $J_2 = 10.0\text{ Hz}$, -CH₂-COO-), 2.04 (s, 3 H, -C(CH₃)=C-), 1.95 (m, 2 H, -CH₂-CH=CH₂), 1.75-1.65 (m, 1 H), 1.48-1.43 (m, 1 H), 1.43-1.36 (m, 1 H), 1.22-1.10 (m, 2 H), 1.17 (s, 3 H, -C(CH₃)₂-), 1.09 (s, 3 H, -C(CH₃)₂-), 1.01 (d, 3 H, $J = 6.5\text{ Hz}$, -C(O)-CH(CH₃)-), 0.86 (s, 9 H, -SiC(CH₃)₃(CH₃)₂), 0.81 (d, 3 H, $J = 7.0\text{ Hz}$, -C(OH)-CH(CH₃)-), 0.09 (s, 3 H, -SiC(CH₃)₃(CH₃)₂), 0.04 (s, 3 H, -SiC(CH₃)₃(CH₃)₂); $^{13}\text{C NMR}$ (125 MHz, CDCl_3): δ = 221.8, 170.9, 164.6, 152.4, 139.0, 136.6, 133.2, 121.0, 117.8, 116.4, 114.1, 78.8, 74.5, 73.4, 53.9, 41.2, 40.1, 37.4, 35.4, 34.1, 32.3, 26.0, 25.9, 21.9, 19.9, 19.2, 18.1, 15.2, 14.6, 9.7, -4.3, -4.9; HRMS calcd for C₃₄H₅₇NO₅SSi ($M+\text{Cs}^+$): 752.2781, found: 752.2760. 13: R_f = 0.21 [silica gel, ethyl acetate : benzene : hexanes (1:2:2)]; $[\alpha]_D = -97$ ($c = 0.2$, MeOH); IR (film): 3456 (br, OH), 1739 (C(O)O), 1692 (COC); $^1\text{H NMR}$ (500 MHz, CDCl_3): δ = 6.94 (s, 1 H, -C=CH-S-), 6.56 (s, 1 H, -C=CH-C=), 5.45 (dd, 1 H, $J_1 = 10.5\text{ Hz}$, $J_2 = 3.0\text{ Hz}$, -CH=CH-CH₂-), 5.35 (m, 1 H, -CH=CH-CH₂-), 5.02 (d, 1 H, $J = 10.0\text{ Hz}$, -O-CH-), 4.06 (dd, 1 H, $J_1 = 7.0\text{ Hz}$, $J_2 = 5.5\text{ Hz}$, -C(CH₃)₂-CH-), 3.94 (bt, 1 H, -CH(OH)-), 3.05 (dq, 1 H, $J_1 = 3.0\text{ Hz}$, $J_2 = 6.5\text{ Hz}$, -C(O)-CH(CH₃)-), 3.00 (bs, 1 H, -OH), 2.82-2.78 (m, 2 H).

2.78-2.69 (m, 1H), 2.71 (s, 3 H, -S-C(CH₃)=N-), 2.40-2.30 (m, 1 H), 2.10 (s, 3 H, -C(CH₃)=CH-C=), 2.10-2.00 (m, 1 H), 1.99-1.90 (m, 1 H), 1.75-1.65 (m, 1 H), 1.7-1.50 (m, 2 H), 1.45-1.35 (m, 1 H), 1.21 (m, 1 H, -CH(CH₃)-CH₂-CH₂-), 1.17 (s, 6 H, -C(CH₃)₂-), 1.14 (d, 3 H, *J* = 5.0 Hz, -C(O)-CH(CH₃)-), 1.02 (d, 3 H, *J* = 5.0 Hz, -CH(CH₃)-), 0.82 (s, 9 H, -SiC(CH₃)₃(CH₃)₂), 0.12 (s, 3 H, -SiC(CH₃)₃(CH₃)₂), 0.05 (s, 3 H, -SiC(CH₃)₃(CH₃)₂); ¹³C NMR (125 MHz, CDCl₃): δ = 218.1, 170.9, 164.7, 138.2, 134.7, 124.0, 119.6, 119.4, 116.0, 79.0, 76.3, 73.2, 53.5, 43.0, 39.1, 38.8, 33.6, 31.9, 28.4, 27.8, 26.1, 24.8, 22.9, 19.2, 18.6, 16.5, 15.3, 14.1, -3.6, -5.5; HRMS calcd for C₃₂H₅₃NO₅SSi (*M* + Cs⁺): 724.2468, found: 724.2479. 1: *R*_f = 0.23 [silica gel, MeOH : CH₂Cl₂ (1:2)]; HPLC [Watman EOC, C-18, 4 μ, 108 x 4.6 mm column, solvent: gradient: 0→20 min, 30→80 % MeOH in H₂O, *R*_t = 14.8 min; [α]_D = -45.0 (*c* = 0.02, MeOH); ¹H NMR (500 MHz, C₆D₆): δ = 6.78 (s, 1 H, -C=CH-S-), 6.52 (s, 1 H, -C=CH-C=), 5.52 (dd, 1 H, *J*₁ = 6.0 Hz, *J*₂ = 2.0 Hz, -O-CH), 4.24 (d, 1 H, *J* = 10.0 Hz, -CH(OH)-), 3.86 (m, 1 H, -CH(OH)), 3.81 (bs, 1 H, -OH), 3.10 (m, 1 H, -CH₂-CHO-), 2.84 (m, 1 H, -C(O)-CH-), 2.67 (m, 1 H, -CH₂-CHO-), 2.49 (dd, 1 H, *J*₁ = 11.0 Hz, *J*₂ = 14.5 Hz, -OOC-CH₂-), 2.27 (s, 3 H, -S-C(CH₃)=N-), 2.24 (dd, 1 H, *J*₁ = 14.5 Hz, *J*₂ = 3.5 Hz, OOC-CH₂-), 2.11 (s, 3 H, -C(CH₃)=), 1.92 (m, 1 H, -CH₂-CHO-), 1.84 (m, 1 H, -CH₂-CHO-), 1.74 (m, 1 H), 1.57 (m, 1 H), 1.27-1.42 (m, 5 H), 1.11 (d, 3 H, *J* = 7.0 Hz, -C(O)-CH(CH₃)-), 1.09 (s, 3 H, -C(CH₃)₂-), 1.03 (s, 3 H, -C(CH₃)₂-), 1.01 (s, 3 H, -CH(CH₃)-); ¹³C NMR (125 MHz, C₆D₆): δ 218.7, 169.9, 164.1, 152.6, 137.2, 119.5, 119.3, 76.3, 74.8, 73.1, 56.9, 53.9, 52.6, 43.4, 38.8, 36.0, 31.4, 30.0, 27.0, 23.6, 20.8, 20.2, 18.4, 17.0, 15.4, 14.3; HRMS calcd for C₂₈H₃₉NO₆S (*M* + Cs⁺): 626.1552, found: 626.1551.

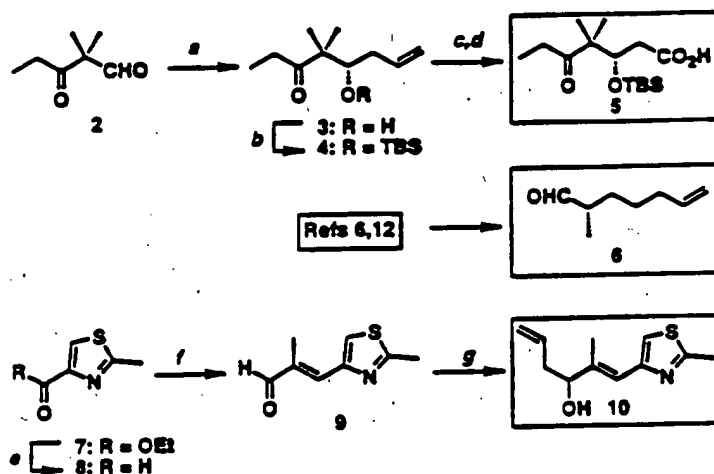
[18] All new compounds exhibited satisfactory spectral and analytical and/or exact

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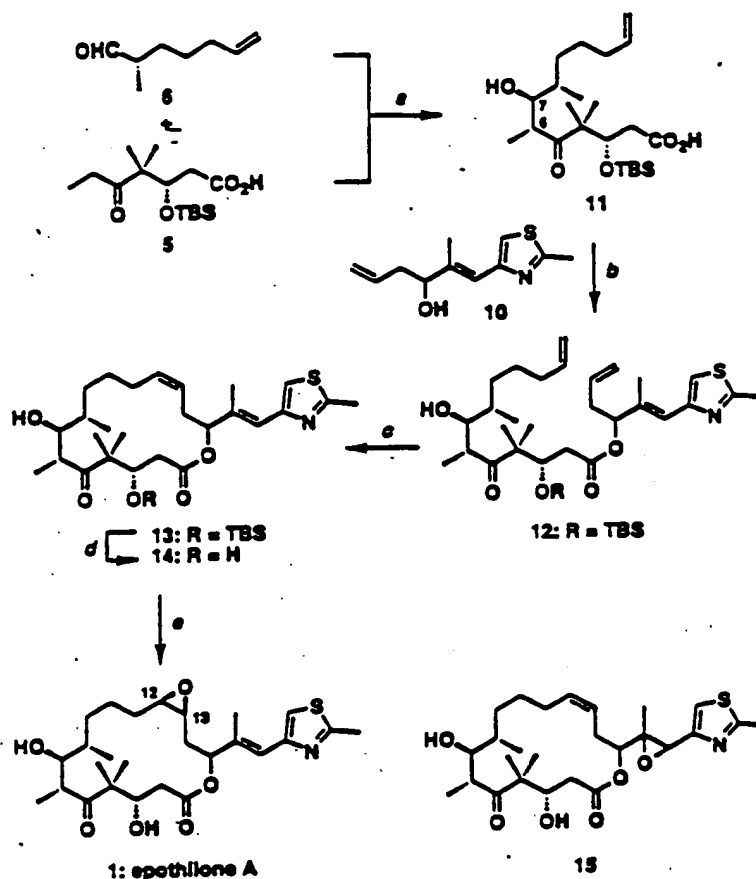


1: epothilone A

Figure 1. Structure and retrosynthetic analysis of epothilone A (1).



Scheme 1. Synthesis of building blocks 5, 6 and 10. a. 1.1 equiv. of (+)-Ipc₂B(allyl), Et₂O, -100 °C, 0.5 h, 74%; b. 1.1 equiv. of TBSOTf, 1.2 equiv. of 2,6-lutidine, CH₂Cl₂, 25 °C, 1 h, 98%; c. O₃, CH₂Cl₂, -78 °C, 0.5 h; then excess Ph₃P, -78 to 25 °C, 1 h, 82%; d. 3 equiv. of NaClO₂, 4 equiv. of 2-methyl-2-butane, 1.5 equiv. of NaH₂PO₄, tBuOH:H₂O (5:1), 25 °C, 2 h, 93%; e. 1.1 equiv. of DIBAL-H, CH₂Cl₂, -78 °C, 0.5 h, 90%; f. 1.1 equiv. of Ph₃P=C(Me)CHO, benzene, 80 °C, 1 h, 90%; g. 1.1 equiv. of (+)-Ipc₂B(allyl), Et₂O, -100 °C, 0.5 h, 98%. TBS = *tert*-butyldimethylsilyl; Ipc₂B(allyl) = diisopinocampheylsilyl borane.



Scheme 2. Synthesis of epothilone A (1): a. 2.2 equiv. of LDA, THF, -78 to -40 °C, 0.5 h; then 1.2 equiv. of 6 in THF, -78 to -40 °C, 0.5 h, high yield of 11 and its 6*S*,7*R*-diastereomer; b. 2.0 equiv. of 10, 1.5 equiv. of DCC, 1.5 equiv. of 4-DMAP, toluene, 25 °C, 12 h, 12 (45% overall yield from 5), plus 6*S*,7*R*-diastereomer of 12 (25% overall yield from 5); c. 12 (0.008 M in CH₂Cl₂), 15 mol % of RuCl₂(=CHPh)(PCy₃)₂ cat., 25 °C, 8 h, 50%, plus Δ^{12,13}-*trans* isomer of 13 (35%); d. CF₃COOH (20% by volume), CH₂Cl₂, 0 °C, 4 h, 98%; e. 1.1 equiv. of *m*CPBA, benzene, 0 °C, 20 h, 1 (55%), plus 12*α*,13*α*-epoxide (20%), plus regioisomeric epoxide 15 (20%). LDA = lithium diisopropylamide, DCC = dicyclohexylcarbodiimide, 4-DMAP = 4-dimethylaminopyridine.

Total Synthesis of Epothilone A: The Macrolactonization Approach[†]

[†] This paper is dedicated to Professor Stephen Hanessian on the occasion of his 60th birthday.

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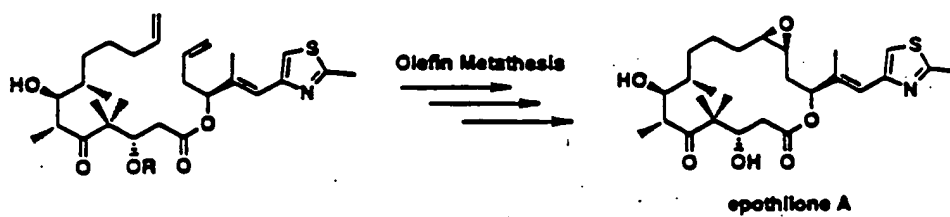
[**] This work was financially supported by The Skaggs Institute of Chemical Biology and the National Institutes of Health (USA). We thank the Fundacion Ramon Areces for a postdoctoral fellowship (F. S.).

Keywords: epothilone, total synthesis, macrolactonization

Table of Content Text

A highly convergent and practical total synthesis of the antitumor agent epothilone A based on a macrolactonization strategy has been developed. The route may lead to a diverse library of epothilones for biological screening.

Scheme.



The novel molecular structures of the epothilones (e.g. epothilone A, 1, Figure 1) coupled with their antifungal^[1,2] and antitumor activities^[1-4] and microtubule binding properties^[4] promise an exciting new chapter in chemistry, biology and medicine. Particularly intriguing is the ability of these compounds to displace taxol from its binding site on microtubules,^[4] towards which they exhibit much higher affinity^[4] than taxol.^[5] An indication of the intense interest in this field is the flurry of activities^[6] directed toward their total synthesis within the relatively short time since their structural elucidation.^[2] While our first total synthesis^[6] of epothilone A (1) enjoys the benefits of the olefin metathesis reaction, the one we wish to report here relies on a macrolactonization process to construct the main ring skeleton of this target molecule. In addition, the reported synthesis is highly convergent and flexible so as to allow entry into a large library of epothilones, including epothilone B and all of the 2⁶ stereoisomers of epothilone A (1).

Figure 1 outlines, in retrosynthetic terms, the macrolactonization approach to epothilone A (1). This analysis leads to a convergent strategy by which three fragments (C₁-C₆, C₇-C₁₂ and C₁₃-C₂₁), each containing a stereogenic center, are to be constructed stereoselectively via asymmetric synthesis procedures followed by their union and elaboration to the final target. For the coupling of these fragments, a Wittig reaction and an aldol reaction will be utilized, whereas the C(O)-O bond formation is reserved as the macrocycle-forming process in the form of a macrolactonization. It is important to note that the designed strategy allows for the preparation of all possible stereoisomers of epothilone A (1) since the configuration of each stereocenter can easily be reversed.

The execution of this rather simple strategy towards epothilone A (1) proceeded smoothly as summarized in Scheme 1. Thus, the SAMP derivative 2, obtained by reaction of SAMP^[7] with propionaldehyde, was alkylated with 4-iodo-1-benzyloxybutane in the presence of LDA in THF at -100 °C according to the method of Enders^[7] +

produce compound 3 in 92% yield and >98% e.e.^[6] Ozonolysis of 3 followed by treatment with NaBH₄ furnished alcohol 5, via aldehyde 4, in 77% overall yield. Protection of the hydroxyl group in 5 as a *tert*-butyldimethylsilyl (TBS) ether followed by standard elaboration of the other end of the molecule (hydrogenolysis of benzyl ether, iodination; and phosphonium salt formation) then yielded the desired fragment 9 in 55% overall yield (from 5).

The second requisite fragment, thiazoline aldehyde 13, was rapidly constructed from the thiazoline derivative 10^[6] by (a): silylation (TBSCl, imidazole, 99%); (b): selective 1,2-dihydroxylation^[9] (AD-mix-β, 79%); and (c): Pb(OAc)₄ cleavage (99%). Generation of the phosphorane 14 from phosphonium salt 9 with sodium hexamethyldisilylamide (NaHMDS), followed by addition of aldehyde 13 led, predominantly, to the *Z*-olefin 15 in 69% yield (*Z:E* ca 9:1). The primary TBS group was selectively removed from 15 with camphorsulfonic acid (CSA) in MeOH to give alcohol 16 (86% yield) which was oxidized to the corresponding aldehyde (17) by the action of SO₃.pyr. (82% yield). Condensation of the dilithioderivative of 18^[6] (2.6 equiv. of LDA, THF, -78 to -40 °C) with aldehyde 17 proceeded at -78 °C to afford a mixture of diastereomers (19 + 6*S,7R*-diastereomer, ca 1:1 to 1:2 ratio, depending on precise conditions) in good yield. This mixture was carried through the sequence until compound 21, at which stage it was separated by silica gel chromatography into its components. Thus, the aldol products (19 + diastereomer) were fully silylated with TBSOTf/2,6-lutidine, and the resulting mixture of *tetra*-TBS derivatives (compound 20 + diastereomer) was briefly exposed to K₂CO₃ in MeOH to afford, after preparative TLC, pure carboxylic acid 21 (31% overall yield), and its 6*S,7R*-diastereomer (30% overall yield from 17) (21: *R*_f = 0.61, 6*S,7R*-diastereomer: *R*_f = 0.70, silica gel, 5% MeOH in CH₂Cl₂). The indicated stereochemical assignment for the slower moving isomer 21 was based on its successful conversion to macrolactone 24^[6] and epothilone A (1).

At this stage, it was necessary to selectively deprotect the C-15 hydroxyl group for the purposes of the intended macrolactonization reaction. This task was successfully accomplished with *tetra-n*-butylammonium fluoride (TBAF) in THF at 25 °C, leading to the desired hydroxy acid 22 in 78% yield. Steric hindrance at the sites of the other TBS groups was presumed to be responsible for this selectivity. The key ring closure of 22 was smoothly effected under Yamaguchi conditions^[10] (2,4,6-trichlorobenzoyl chloride, Et₃N, 4-DMAP, THF-toluene, 25 °C) furnishing the 16-membered ring lactone 23 in 90% yield. Finally, exposure of 23 to CF₃COOH (20% by volume) in CH₂Cl₂ at 0 °C led to the targeted olefinic diol 24 (92% yield). The latter compound was then converted to epothilone A (1) by exposure to *m*CPBA as already described.^[6]

This expedient route to epothilone A (1) may easily be extended to epothilone B and to a variety of analogs of these naturally occurring compounds for biological investigations. Indeed, the molecular design, chemical synthesis and biological screening of such analogs should be among the next priorities in this field.^[11]

Table 1. Selected physical properties of compounds 21, 22 and 23.

21: R_f = 0.61 [silica gel, methanol:dichloromethane (5%)]; $[\alpha]_D^{22}$ = -8.8 (c = 0.8 in chloroform); IR (film): 2931, 2856, 1712, 1466, 1254, 1083, 836 cm⁻¹; ¹H-NMR (600 MHz, CDCl₃): δ = 6.94 (s, 1 H, -C=CH-S-), 6.61 (s, 1 H, -C=CH-C=), 5.44-5.41 (m, 2 H, -CH=CH-CH₂-, -CH=CH-CH₂-), 4.40 (dd, 1 H, J_1 = 3.2 Hz, J_2 = 6.5 Hz, -(CH₃)₂C-CH-), 4.11 (dd, 1 H, J_1 = 5.9 Hz, J_2 = 6.5 Hz, -CH(OSi(CH₃)₂*t*-Bu)-), 3.75 (dd, 1 H, J_1 = 3.0 Hz, J_2 = 6.5 Hz, TBSO-CH-CH(Me)), 3.12 (dq, 1 H, J_1 = 7.0 Hz, J_2 = 6.5 Hz, -C(O)-CH(CH₃)-), 2.69 (s, 3 H, -S-C(CH₃)=N-), 2.48 (dd, 1 H, J_1 = 3.2 Hz, J_2 = 16.0 Hz, -CH₂-COOH), 2.35 (dd, 1 H, J = 6.7 Hz, J = 16.0 Hz, -CH₂-COOH), 2.31-2.28 (m, 2 H, -CH₂-CH=CH), 2.10-2.00 (m, 2 H, -CH₂-CH=CH), 1.95 (s, 3 H, -C(CH₃)=CH-C=), 1.42-1.30 (m, 5 H, -C(CH₃)₂-), 1.30 (s, 3 H, -C(CH₃)₂-), 1.10 (s, 3 H, -C(CH₃)₂-), 1.06 (d, 3 H, J = 7.0 Hz, -

$\text{C(O)-CH(CH}_3\text{)-}$, 0.90-0.85 (m, 30 H, $\text{-C(O)-CH(CH}_3\text{)-}$, 3 x $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.12 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.09 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.07 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.05 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.04 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.03 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$); $^{13}\text{C-NMR}$ (600 MHz, CDCl_3): δ : 218.2, 176.1, 164.9, 152.7, 142.8, 131.4, 126.0, 118.5, 114.7, 78.7, 73.3, 53.7, 44.7, 40.0, 39.0, 34.7, 30.8, 28.0, 27.8, 26.2, 26.0, 25.8, 23.6, 19.0, 18.8, 18.5, 18.2, 17.2, 15.8, 13.8, -3.8, -3.9, -4.2, -4.6, -4.7, -4.9; HRMS calcd for $\text{C}_{44}\text{H}_{83}\text{NO}_6\text{SSi}_3$ ($M + \text{Cs}^+$); 970.4303, found: 970.4318.

22: $R_f = 0.40$ [silica gel, methanol:dichloromethane (5%)]; $[\alpha]^{22}_D = -19.2$ ($c = 0.1$ in chloroform); IR (film): 3358 (br, OH), 2932, 2857, 1701, 1466, 1254, 1088, 988, 835; $^1\text{H-NMR}$ (600 MHz, CDCl_3): δ = 6.95 (s, 1 H, -C=CH-S-), 6.61 (s, 1 H, -C=CH-C=), 5.58-5.54 (m, 1 H, $\text{-CH=CH-CH}_2\text{-}$), 5.43-5.39 (m, 1 H, $\text{-CH=CH-CH}_2\text{-}$), 4.39 (dd, 1 H, $J_1 = 3.9$ Hz, $J_2 = 6.7$ Hz, $\text{-(CH}_3\text{)}_2\text{C-CH-}$), 4.18 (dd, 1 H, $J_1 = 5.0$ Hz, $J_2 = 7.5$ Hz, -CH(OH)-), 3.78 (dd, 1 H, $J_1 = 3.0$ Hz, $J_2 = 6.9$ Hz, -SiO-CH-CH(Me)-), 3.11 (dq, 1 H, $J_1 = 6.9$ Hz, $J_2 = 6.7$ Hz, $\text{-C(O)-CH(CH}_3\text{)-}$), 2.70 (s, 3 H, $\text{-S-C(CH}_3\text{)=N-}$), 2.43 (dd, 1 H, $J_1 = 3.9$ Hz, $J_2 = 16.2$ Hz, $\text{-CH}_2\text{-COOH}$), 2.40-2.35 (m, 2 H, $\text{-CH}_2\text{-CH=}$), 2.35 (dd, 1 H, $J_1 = 6.7$ Hz, $J_2 = 16.2$ Hz, $\text{-CH}_2\text{-COOH}$), 2.15-2.10 (m, 1 H, $\text{-CH}_2\text{-CH=}$), 2.00 (s, 3 H, $\text{-C(CH}_3\text{)=CH-C=}$), 1.99-1.95 (m, 1 H, $\text{-CH}_2\text{-CH=}$), 1.48-1.30 (m, 5 H), 1.18 (s, 3 H, $\text{-C(CH}_3\text{)}_2\text{-}$), 1.08 (s, 3 H, $\text{-C(CH}_3\text{)}_2\text{-}$), 1.05 (d, 3 H, $J = 6.7$ Hz, $\text{-C(O)-CH(CH}_3\text{)-}$), 0.89-0.84 (m, 21 H, $\text{-C(O)-CH(CH}_3\text{)-}$, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.09 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.05 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.04 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$), 0.03 (s, 3 H, $\text{-SiC(CH}_3\text{)}_3\text{(CH}_3\text{)}_2$); $^{13}\text{C-NMR}$ (600 MHz, CDCl_3): δ : 218.9, 175.4, 166.3, 152.8, 134.4, 125.7, 119.5, 115.9, 74.4, 74.3, 54.7, 45.5, 40.9, 40.0, 34.3, 31.9, 30.6, 28.9, 28.8, 27.0, 26.9, 24.4, 22.0, 21.4, 20.0, 19.6, 19.3, 19.1, 17.9, 17.1, 15.5, 8.6, -2.9, -3.1, -3.3, -3.8; HRMS calcd for $\text{C}_{38}\text{H}_{69}\text{NO}_6\text{SSi}_2$ ($M + \text{Cs}^+$); 856.3439, found: 856.3459.

23: $R_f = 0.37$ [silica gel, hexane : ether (2:1)]; $[\alpha]^{22}_D = -22.9$ ($c = 0.3$ in chloroform); IR (film): 2926, 2854, 1734, 1693, 1463, 1381, 1252, 1099, 829; $^1\text{H-NMR}$ (500 MHz, CDCl_3): δ = 6.98 (s, 1 H, -C=CH-S-), 6.58 (s, 1 H, -C=C: I-C=), 5.53 (m, 1 H, -CH=CH-

CH₂), 5.43-5.34 (m, 1 H, -CH=CH-CH₂-), 5.00 (d, 1 H, $J = 6.0$ Hz, -O-CH), 4.03 (d, 1 H, $J = 10.0$ Hz, -CH(OH)-), 3.89 (d, 1 H, $J = 9.0$ Hz, -CH(OH)), 3.04-2.98 (m, 1 H, -C(O)-CH-), 2.85 (d, 1 H, $J = 15.0$ Hz, OOC-CH₂-), 2.72 (s, 3 H, -S-C(CH₃)=N-), 2.66 (dd, 1 H, $J_1 = 15.0$ Hz, $J_2 = 10.0$ Hz, OOC-CH₂-), 2.42-2.31 (m, 2 H), 2.11 (s, 3 H, -C(CH₃)=), 1.92-1.83 (m, 1 H), 1.66-1.38 (m, 4 H), 1.20 (s, 3 H, -C(CH₃)₂-), 1.16 (s, 3 H, -C(CH₃)₂), 1.09 (d, 3 H, $J = 7.0$ Hz, -C(O)-CH(CH₃)-), 0.95 (d, 3 H, $J = 7.0$ Hz, -CH(CH₃)-), 0.94 (s, 9 H, -SiC(CH₃)₃(CH₃)₂), 0.85 (s, 9 H, -SiC(CH₃)₃(CH₃)₂), 0.12 (s, 3 H, -SiC(CH₃)₃(CH₃)₂), 0.10 (s, 3 H, -SiC(CH₃)₃(CH₃)₂), 0.08 (s, 3 H, -SiC(CH₃)₃(CH₃)₂), -0.10 (s, 3 H, -SiC(CH₃)₃(CH₃)₂). ¹³C-NMR (600 MHz, C₆D₆): δ : 215.0, 171.3, 135.1, 122.7, 79.5, 76.4, 53.3, 48.0, 38.8, 31.7, 29.7, 29.2, 28.4, 26.4, 26.2, 26.1, 25.0, 24.2, 19.1, 18.7, 18.6, 17.7, 15.3, -3.1, -3.2, -3.7, -5.8; HRMS calcd for C₃₈H₆₇NO₅SSi₂ ($M + H^+$); 706.4357, found: 706.4382.

References

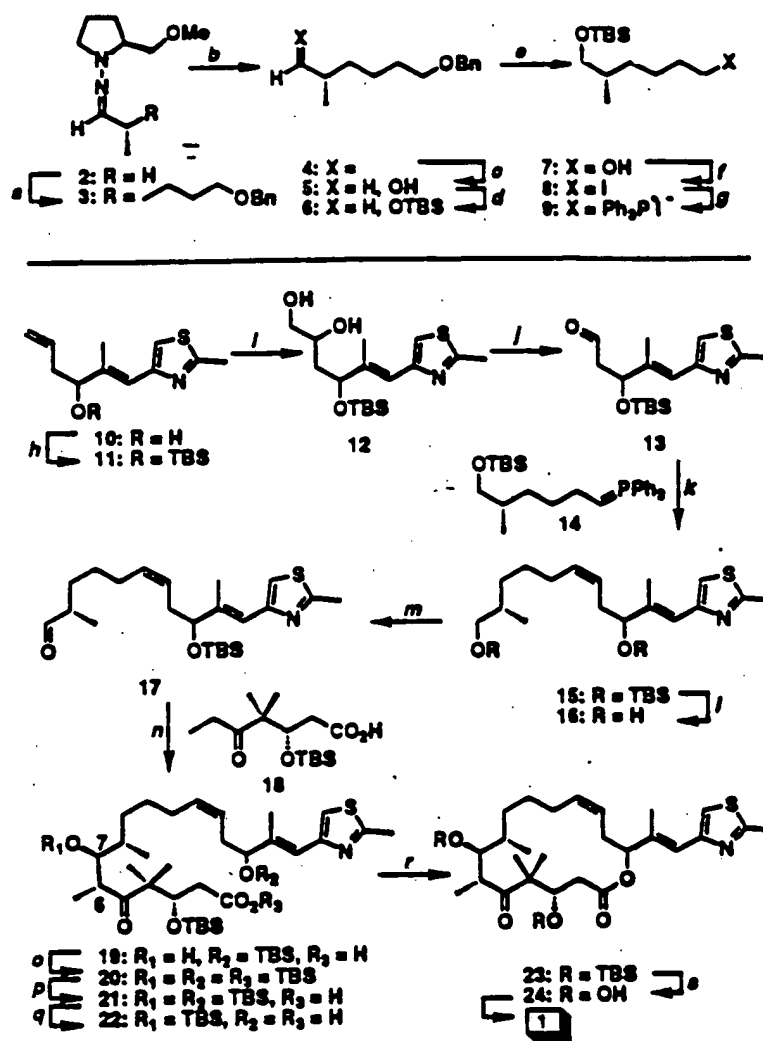
- [1] a) G. Höfle, N. Bedorf, K. Gerth, H. Reichenbach (GBF), DE-4138042, 1993 (*Chem. Abstr.* 1993, 120, 52841); b) K. Geth, N. Bedorf, G. Höfle, H. Irschik, H. Reichenbach, *J. Antibiot.* 1996, 49, 560-563.
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H. Khatuya, P. B. rtinato, R. A. Miller, M. J. Tomaszewski: *Chem. Eur. J.* 1996, 2, 847-868.

- [11] All new compounds exhibited satisfactory spectral and analytical and/or exact mass data.

Scheme 1. Total synthesis of epothilone A (1): a. 1.1 equiv. of LDA, THF, 0 °C, 8 h; then 1.5 equiv. of 4-iodo-1-benzyloxybutane in THF, at -100 to 0 °C, 6 h, 92%; b. O₃, CH₂Cl₂, -78 °C, 77%; c. 3.0 equiv. of NaBH₄, MeOH, 0 °C, 15 min, 98 %; d. 1.5 equiv. of TBSCl, 2.0 equiv. of Et₃N, CH₂Cl₂, 0 °C to 25 °C, 12 h, 95%; e. H₂, Pd(OH)₂ cat., THF, 3 h, 25 °C, 70%; f. 1.5 equiv. of I₂, 3.0 equiv. of imidazole, 1.5 equiv. of Ph₃P, Et₂O/CH₃CN [3 : 1], 0 °C, 0.5 h, 91%; g. Ph₃P, neat, 100 °C, 2 h, 86%; h. 1.5 equiv. of TBSCl, 2.0 equiv. of imidazole, THF, 0 to 25 °C, 1 h, 99%; i. 2.4 g/mmol of AD-mix-β, *t*-BuOH/H₂O [1 : 1], 25 °C, 8 h, 79%; j. 1.1 equiv. of Pb(OAc)₄, EtOAc, 0 °C, 10 min, 99%; k. 1.2 equiv. of 9, 1.2 equiv. of NaHMDS, THF, 0 °C, 0.25 h, then add 1.0 equiv. of aldehyde 13, 0 °C, 15 min, 69% (*Z* : *E* ca. 9 : 1); l. 1.0 equiv. of CSA portionwise over 1 h, CH₂Cl₂/MeOH [1 : 1], 0 °C, then 25 °C, 0.5 h, 86%; m. 2.0 equiv. of SO₃.pyr., 10.0 equiv. of DMSO, 5.0 equiv. of Et₃N, CH₂Cl₂, 25 °C, 0.5 h, 82%; n. 3.0 equiv. of LDA, THF, 0 °C, 0.25 h; then 1.2 equiv. of 18 in THF, -78 to -40 °C, 0.5 h, then 1.0 equiv. of 17 in THF at -78 °C, high yield of 19 and its 6*S*,7*R*-diastereomer (ca. 1 : 1 ratio); o. 3.0 equiv. of TBSOTf, 5.0 equiv. of 2,6-lutidine, CH₂Cl₂, 0 °C, 2 h; p. 2.0 equiv. of K₂CO₃, MeOH, 25 °C, 15 min, 31% of 21 and 30% of its 6*S*,7*R*-diastereomer from 17; q. 6.0 equiv. of TBAF, THF, 25 °C, 8 h, 78%; r. 5 equiv. of 2,4,6-trichlorobenzoylchloride, 6.0 equiv. of Et₃N, THF, 25 °C, 15 min, then add to a solution of 10.0 equiv. of 4-DMAP in toluene (0.002 M based on 22), 25 °C, 0.5 h, 90%; s. 20% CF₃COOH [by volume] in CH₂Cl₂, 0 °C, 1 h, 92%. LDA = lithium diisopropylamide; 4-DMAP = 4-dimethylaminopyridine; TBS = *tert*-butyldimethylsilyl; NaHMDS = sodium hexamethyldisilamide; DMSO = dimethylsulfoxide; Tf = triflate.



Scheme 1

Scheme 1. Total synthesis of epothilone A (1): a. 1.1 equiv. of LDA, THF, 0 °C, 8 h; then 1.5 equiv. of 4-iodo-1-benzyloxybutane in THF, at -100 to 0 °C, 6 h, 92%; b. O₃, CH₂Cl₂, -78 °C, 77%; c. 3.0 equiv. of NaBH₄, MeOH, 0 °C, 15 min, 98 %; d. 1.5 equiv. of TBSCl, 2.0 equiv. of Et₃N, CH₂Cl₂, 0 °C to 25 °C, 12 h, 95%; e. H₂, Pd(OH)₂ cat., THF, 3 h, 25 °C, 70%; f. 1.5 equiv. of I₂, 3.0 equiv. of imidazole, 1.5 equiv. of Ph₃P, Et₂O/CH₃CN [3 : 1], 0 °C, 0.5 h, 91%; g. Ph₃P, neat, 100 °C, 2 h, 86%; h. 1.5 equiv. of TBSCl, 2.0 equiv. of imidazole, THF, 0 to 25 °C, 1 h, 99%; i. 2.4 g/mmol of AD-mix-β, *t*-BuOH/H₂O [1 : 1], 25 °C, 8 h, 79%; j. 1.1 equiv. of Pb(OAc)₄, EtOAc, 0 °C, 10 min, 99%; k. 1.2 equiv. of 9, 1.2 equiv. of NaHMDS, THF, 0 °C, 0.25 h, then add 1.0 equiv. of aldehyde 13, 0 °C, 15 min, 69% (*Z* : *E* ca. 9 : 1); l. 1.0 equiv. of CSA portionwise over 1 h, CH₂Cl₂/MeOH [1 : 1], 0 °C, then 25 °C, 0.5 h, 86%; m. 2.0 equiv. of SO₃.pyr., 10.0 equiv. of DMSO, 5.0 equiv. of Et₃N, CH₂Cl₂, 25 °C, 0.5 h, 82%; n. 3.0 equiv. of LDA, THF, 0 °C, 0.25 h; then 1.2 equiv. of 18 in THF, -78 to -40 °C, 0.5 h, then 1.0 equiv. of 17 in THF at -78 °C, high yield of 19 and its 6*S*,7*R*-diastereomer (ca. 1 : 1 ratio); o. 3.0 equiv. of TBSOTf, 5.0 equiv. of 2,6-lutidine, CH₂Cl₂, 0 °C, 2 h; p. 2.0 equiv. of K₂CO₃, MeOH, 25 °C, 15 min, 31% of 21 and 30% of its 6*S*,7*R*-diastereomer from 17; q. 6.0 equiv. of TBAF, THF, 25 °C, 8 h, 78%; r. 5 equiv. of 2,4,6-trichlorobenzoylchloride, 6.0 equiv. of Et₃N, THF, 25 °C, 15 min, then add to a solution of 10.0 equiv. of 4-DMAP in toluene (0.002 M based on 22), 25 °C, 0.5 h, 90%; s. 20% CF₃COOH [by volume] in CH₂Cl₂, 0 °C, 1 h, 92%. LDA = lithium diisopropylamide; 4-DMAP = 4-dimethylaminopyridine; TBS = *tert*-butyldimethylsilyl; NaHMDS = sodium hexamethyldisilylamide; DMSO = dimethylsulfoxide; Tf = triflate.

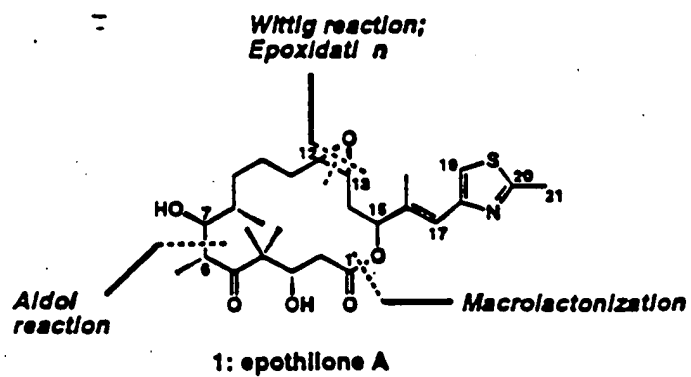
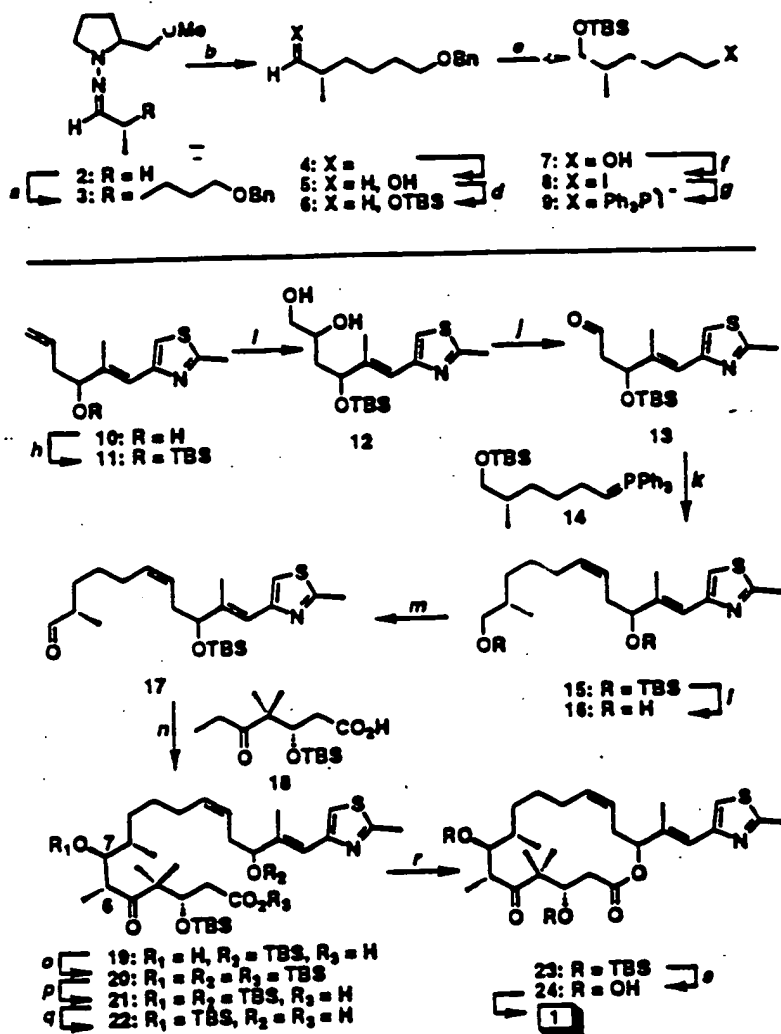
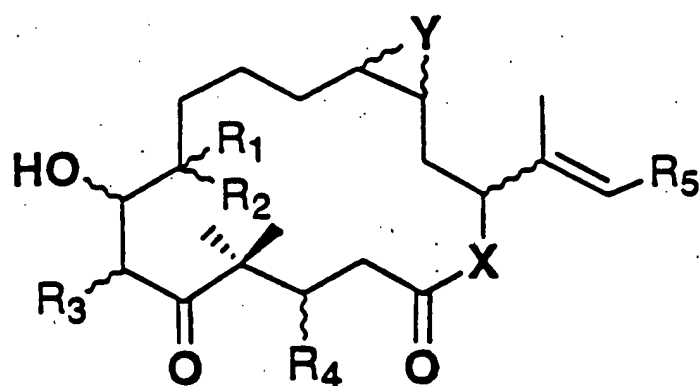
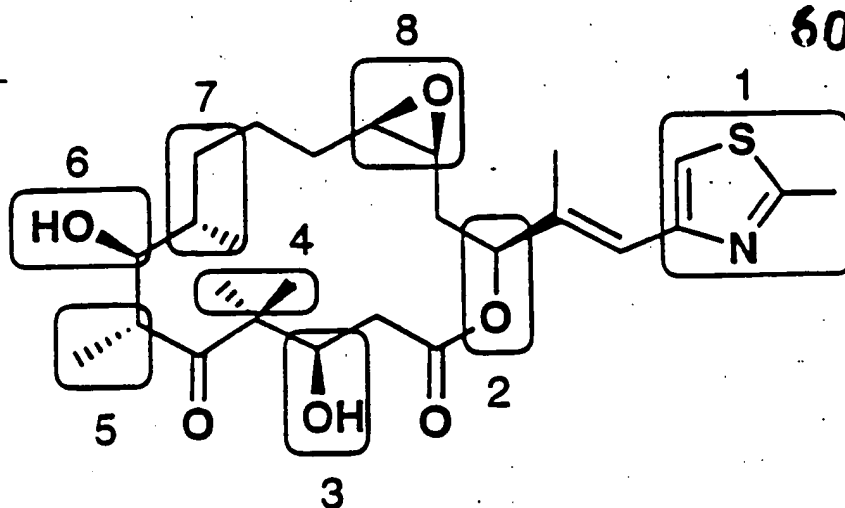


Figure 1. Structure and retrosynthetic analysis of epothilone A (1).

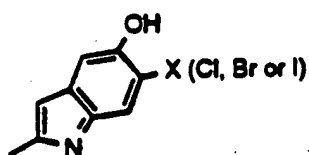
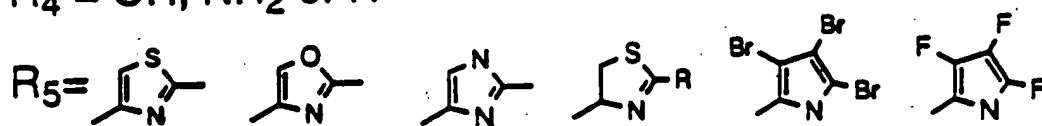


Scheme 1. Total synthesis of epothilone A (1): a. 1.1 equiv. of LDA, THF, 0 °C, 8 h; then 1.5 equiv. of 4-iodo-1-benzoyloxybutane in THF, at -100 to 0 °C, 8 h, 92%; b. O₃, CH₂Cl₂, -78 °C, 77%; c. 3.0 equiv. of NaBH₄, MeOH, 0 °C, 15 min, 98%; d. 1.5 equiv. of TBSCl, 2.0 equiv. of Et₃N, CH₂Cl₂, 0 °C to 25 °C, 12 h, 95%; e. H₂, Pd(OH)₂ cat., THF, 3 h, 25 °C, 70%; f. 1.5 equiv. of I₂, 3.0 equiv. of imidazole, 1.5 equiv. of Ph₃P, Et₂O/CH₂Cl₂ (3 : 1), 0 °C, 0.5 h, 91%; g. Ph₃P, neat, 100 °C, 2 h, 86%; h. 1.5 equiv. of TBSCl, 2.0 equiv. of imidazole, THF, 0 to 25 °C, 1 h, 98%; i. 2.4 g/mmol of AD-mix- α , ^tBuOH/H₂O (1 : 1), 25 °C, 8 h, 79%; j. 1.1 equiv. of Pb(OAc)₄, EtOAc, 0 °C, 10 min, 99%; k. 1.2 equiv. of 9, 1.2 equiv. of NaHMDS, THF, 0 °C, 0.25 h, then add 1.0 equiv. of aldehyde 13, 0 °C, 15 min, 69% (Z : E ca. 9 : 1); l. 1.0 equiv. of CSA portionwise over 1 h, CH₂Cl₂/MeOH (1 : 1), 0 °C, then 25 °C, 0.5 h, 86%; m. 2.0 equiv. of SO₂, pyr., 10.0 equiv. of DMSO, 5.0 equiv. of Et₃N, CH₂Cl₂, 25 °C, 0.5 h, 82%; n. 3.0 equiv. of LDA, THF, 0 °C, 0.25 h; then 1.2 equiv. of 18 in THF, -78 to -40 °C, 0.5 h, then 1.0 equiv. of 17 in THF at -78 °C, high yield of 19 and its 6S,7R-diastereomer (ca. 1 : 1 ratio); o. 3.0 equiv. of TBSOTf, 5.0 equiv. of 2,6-lutidine, CH₂Cl₂, 0 °C, 2 h; p. 2.0 equiv. of K₂CO₃, MeOH, 25 °C, 15 min, 31% of 21 and 30% of its 6S,7R-diastereomer from 17; q. 6.0 equiv. of TBAF, THF, 25 °C, 8 h, 78%; r. 5 equiv. of 2,4,6-tri-*t*-butoxybenzoylchloride, 6.0 equiv. of Et₃N, THF, 25 °C, 15 min, then add to s. s. 0.0 equiv. of 4-DMAP in toluene (0.002 M based on 22), 25 °C, 0.5 h, 90%; t. 20% CH₃COOH [by volume] in CH₂Cl₂, 0 °C, 1 h, 92%. LDA = lithium diisopropylamide; 4-DMAP = 4-dimethylaminopyridine; TBS = *tert*-butyldimethylsilyl; NaHMDS = sodium hexamethyldisilazide; DMSO = dimethylsulfoxide; Tf = triflate.

60/032864



$R_1 = \text{Me, Et or H}$
 $R_2 = \text{Me, Et or H}$
 $R_3 = \text{Me, Et, or MeOR}$
 $R_4 = \text{OH, NH}_2 \text{ or H}$

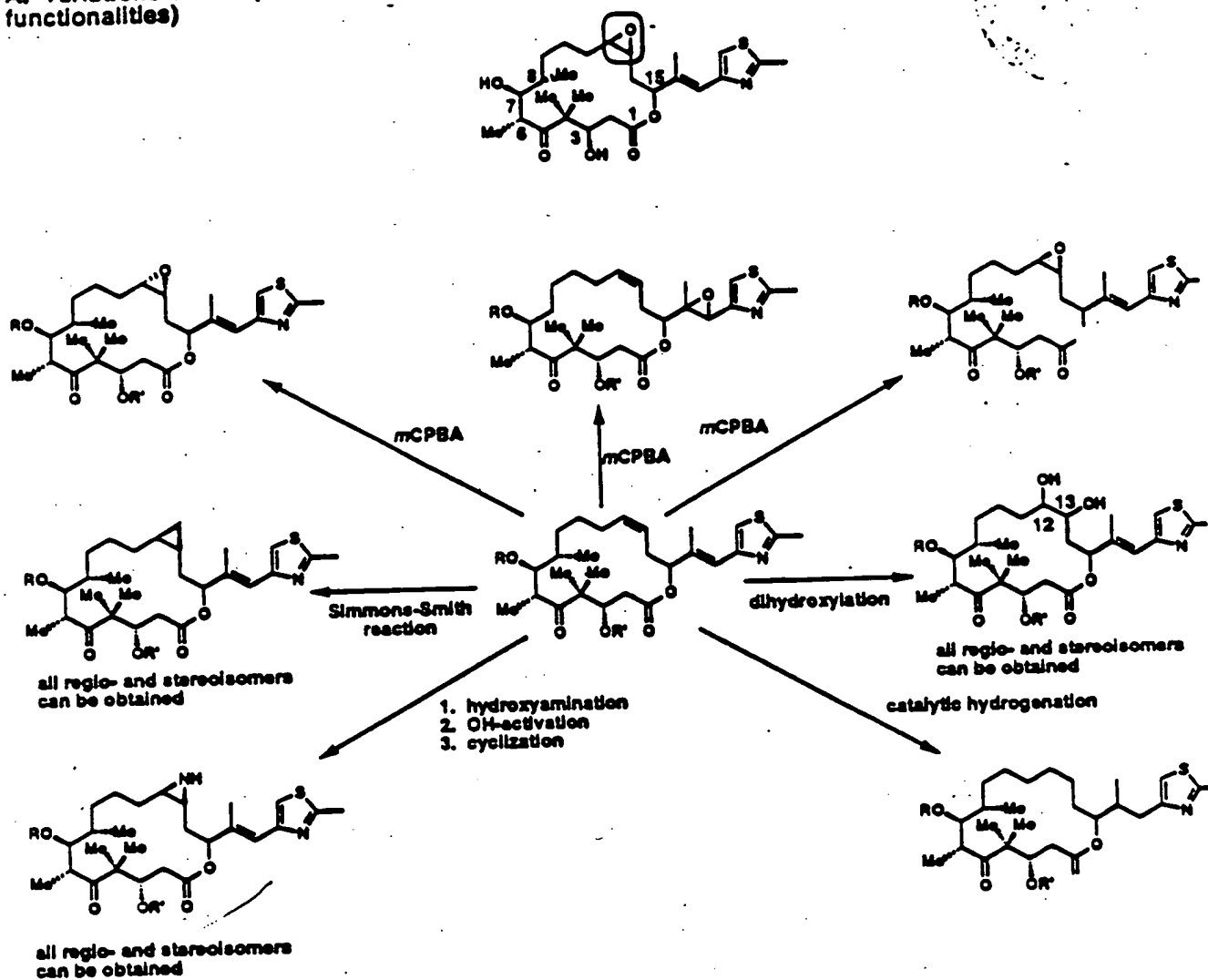


$X = \text{O, NH}$
 $Y = \text{O, N, CH}_2$

Figure 1

60/032664

A. Variations of the epoxide functionality (stereoisomers, regioisomers, other functionalities)



R is selected from the group consisting of H, methyl, n-alkyl, acyl, allyl, benzyl.

FIGURE 2

Variation of the side chain

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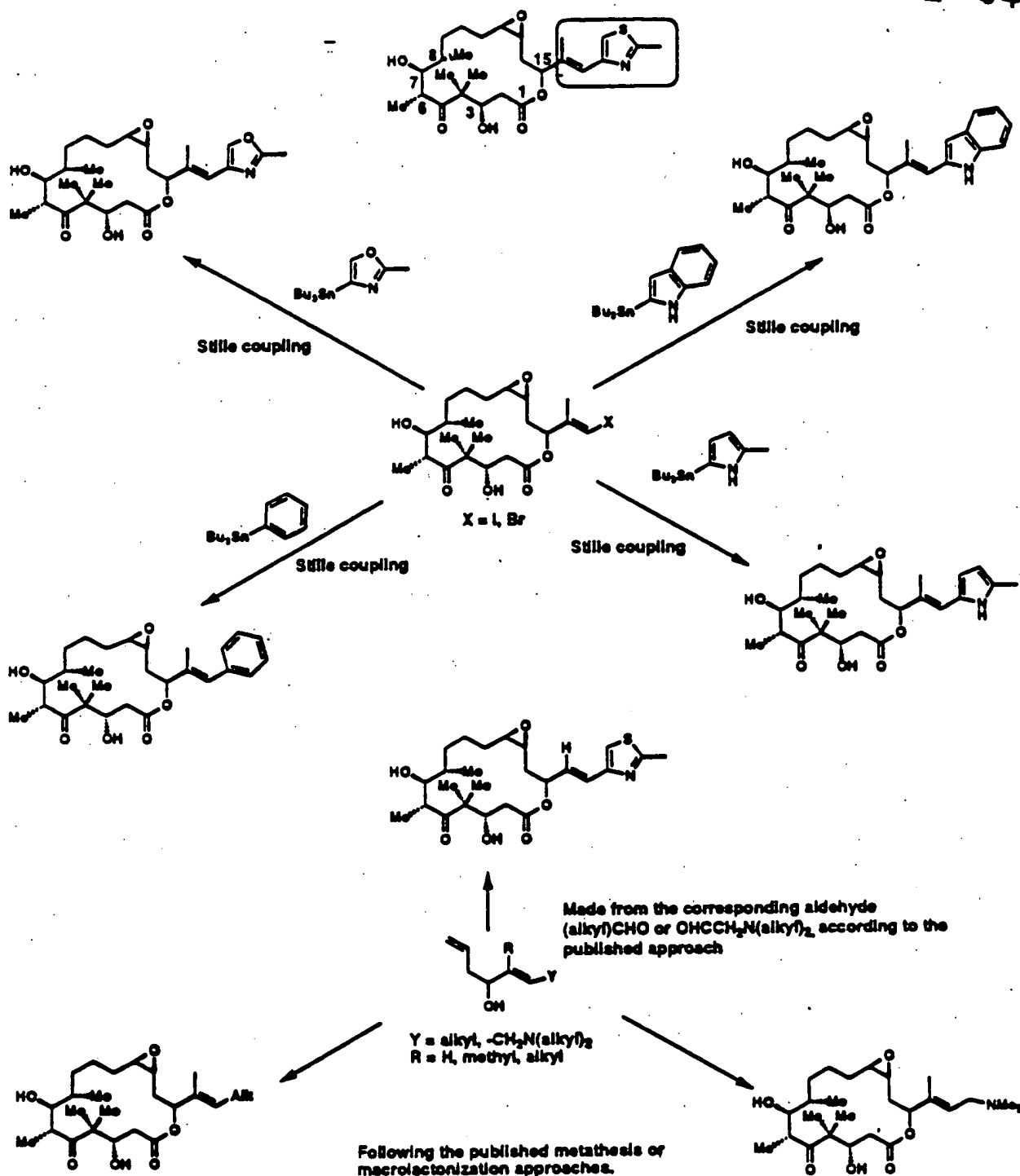
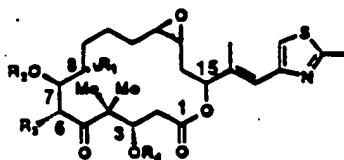


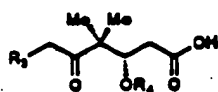
Figure 5

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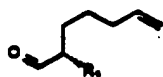
C. Synthesis of all possible stereoisomers at carbons 3, 5, 7, 8 and 15.



All different isomers can be obtained by the established route.
 $R_2, R_4 = H, Me, n\text{-Alkyl, Silyl, Benzyl}$
 $R_1, R_3 = H, n\text{-Alkyl}$



made from different acyl chlorides by the published procedure



synthesized by Oppolzar's protocol as the original α -methyl aldehyde

Figure 4

D. Variations of the gem-dimethyl functionality

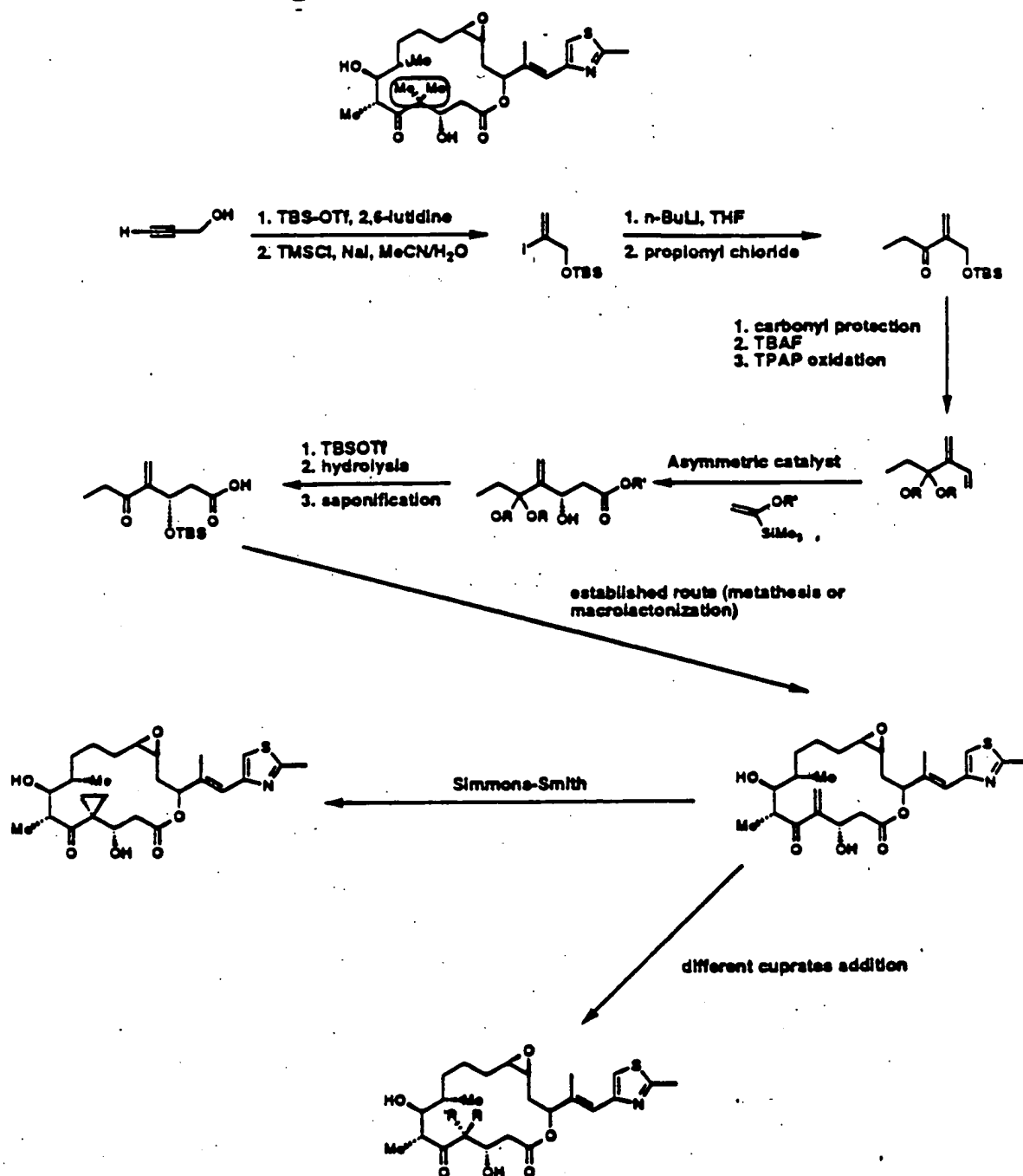


Figure 5

E. Variations of the ring side

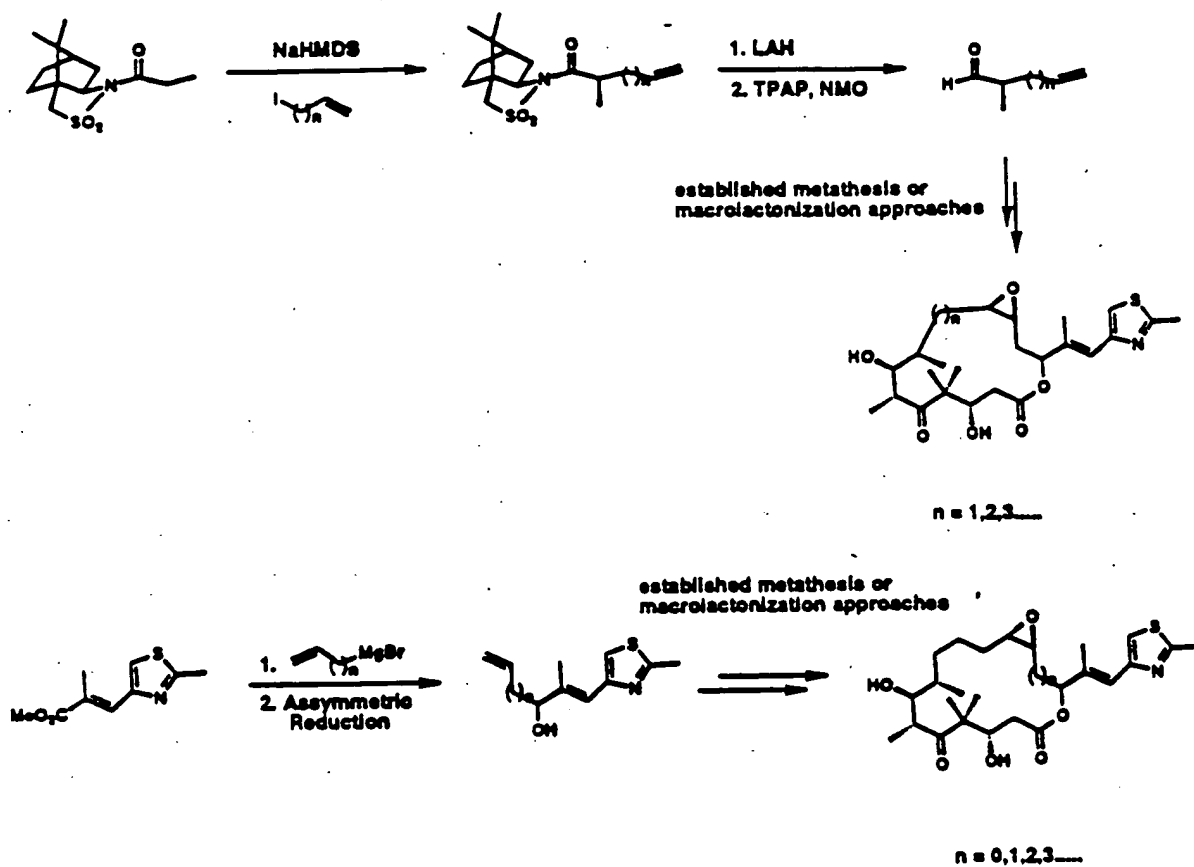


Figure 6

F. Generation of epothilone-taxoids hybrids

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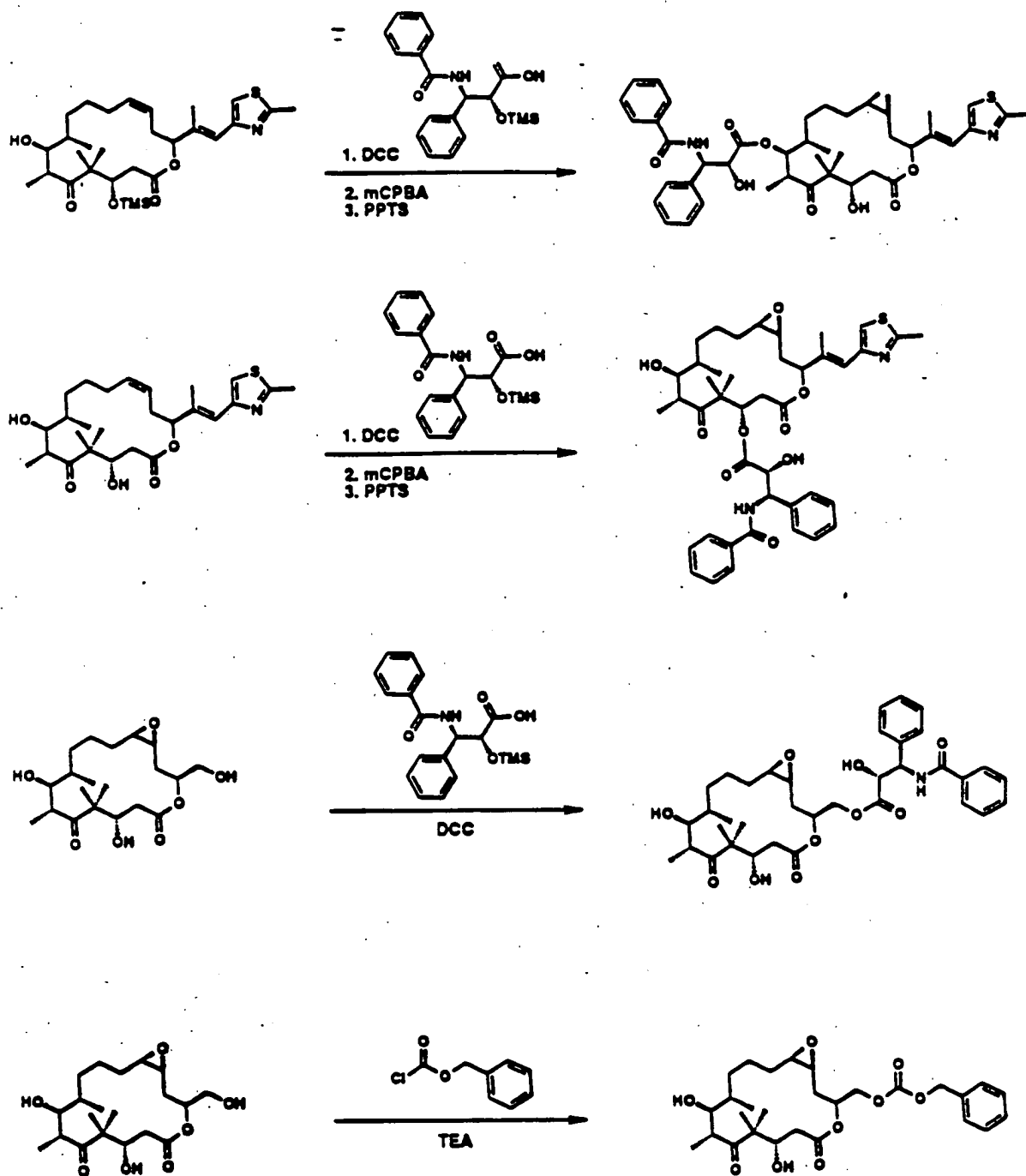


Figure 7

